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Water security in high mountain cities of the Andes under a growing population and climate change: A case study of La Paz and El Alto, Bolivia

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ABSTRACT

Water resources in La Paz and El Alto, Bolivia strongly depend on runoff from mountain catchments in the Cordillera Real, Andes. The balance between the water available from the source catchments and the demand of the cities has become precarious during recent years because of an increasing population and the runoff variability caused by climate change. In this study, a first-order estimate of the future water supply and demand for the El Alto system, the most rapidly growing area in La Paz and El Alto, was obtained for the first time based on a demographic analysis and runoff projection, and effective measures for adapting to water shortage were examined. The water demand in 2036 is expected to increase by 15–53% compared to that of 2011, depending on the scenario for the water loss in the supply system and population estimates, while the projected water supply shows frequent reductions because of the climate variability and decreasing glacial meltwater. Thus, the water transfer from a neighboring system (the Achachicala system) will be indispensable to sustain the supply that cannot be covered by releases from Tuni Lake. Nevertheless, the El Alto system will likely face a serious water shortage after the mid-2020s for the most conservative scenario of demand increase, while large uncertainty was found for the balance of supply and demand, depending on the scenarios for population growth, improvement of water loss, and climate variability and trend. For supply side management, the extended diversion of runoff into Tuni Lake, water transfer from the Achachicala system, and transfer of runoff from the Taypichaca catchment will be effective in securing the water supply under various uncertain conditions.

1. Introduction

Water resources are a significant element in human settlement and social and economic development at a regional scale, and are becoming globally important because of the strong global linkage with food and energy security (e.g., [46,47,10]. It is projected that water scarcity will progress globally, particularly in regions where large populations occur and/or there is a shift to drier climatic conditions with decreased precipitation as predicted (e.g., [1,4].

Among the regions where water scarcity is already acute, the Pacific coastal plains and western slopes along the Andes in Bolivia, Chile, Ecuador and Peru, where a majority of the population and economic activity occur, are susceptible to climate change and the resultant impacts on water resources [3]. It is recognized that the region depends partly on water resources resulting from the melting of a large number of glaciers distributed at high altitudes in the Andes [42,39]. However, glaciers in high altitudinal tropical regions are thought to be strongly affected by global warming [3], thus they are expected to undergo remarkable retreats [44,21,31], decreasing total volume of streamflow [14] and intensifying streamflow seasonality [17,18].

It is recognized that much of the future water scarcity may be caused primarily by the demand side [45]. Buytaert and de Bievre [6] analyzed future per capita water availability for major cities in the tropical Andes, and showed that the expected demographic changes are very likely to outpace the impact of climate change on water availability. Because the region will experience a high rate of population growth and the accompanying increase in water demand (e.g., [1], it is also likely that the influence of a changing climate will be more serious for water security throughout the region. Carey et al. [8] emphasized the necessity of a holistic hydro-social framework via integrated analysis of both water availability and water use through a case study of the Santa River, Peru. Drenkhan et al. [11] reviewed hydroclimatic and

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socioeconomic drivers of water resources in two major catchments in the Peruvian Andes, suggesting the need to better link water supply with demand research.

Among areas considered as water scarce in the Andean region, we attempted to analyze the influence of climate change and population growth on the water security of the administrative capital of Bolivia, La Paz, and the rapidly developing adjacent city, El Alto, located on the Altiplano. The cities are dependent for most of their water use on streamflow from catchments in the Cordillera Real, Andes. However, the area has experienced a strong increase in drought severity during the period 1985–2012, because of a higher reference evapotranspiration [43]. Furthermore, as the demand has been increasing during recent years (Ministry of Environment and Water, Bolivia [MMAyA], [24]), particularly in the fast-growing city of El Alto, temporary water rationing has been enacted. Because the El Niño-Southern Oscillation plays a significant role in precipitation over the Bolivian Andes [43], in addition to the influence of the Amazon, the area experienced its worst drought in 25 years because of an El Niño episode during 2015 and 2016. Bolivia's government declared a state of emergency in November 2016 because of the significant water shortage. This climatic and social evidence and pressure on future water resources in La Paz and El Alto necessitate a detailed analysis of future water supply and demand to prepare for water scarcity under a changing climate and growing population.

As the increase in population is likely to continue, and more water resources will be required for La Paz and El Alto, a study of the demand side projection and adaptation to the deficit of water supply for these cities is urgently needed. Therefore, reliable future growth projections based on more detailed population dynamic models need to be pursued to evaluate the impact on water resources [6].

On the supply side, glaciers annually contribute 15% of the water resources for La Paz and more during the dry season [39]. Because glaciers in Bolivia as well as in Peru and Ecuador have been rapidly retreating [32,12,38,21,36,45] and continuous retreat is anticipated [45], the future water availability for La Paz and El Alto needs to be projected with more focus on the non-glacier origin of streamflow. However, compared to studies reported for the Cordillera Blanc, Peru (e.g., [17,9,22], limited papers have been published on catchment-scale water resources in the Bolivian Andes considering glacial and non-glacial runoff components (e.g., [7,39], despite the imminent threat of water scarcity in La Paz and El Alto.

Therefore, this study attempted for the first time to provide a first-order estimate of the future water supply and demand for La Paz and El Alto and suggests adaptive measures to secure water resources by analyzing future demographic changes and the glacio-hydrological response of source catchments under a changing climate, considering the actual water supply systems in these cities.

2. Study area and methodology

2.1. Study area

The water supply for La Paz and El Alto is dependent on four drinking water systems (Fig. 1). The El Alto, Achachicala, and Pampahasi systems are based on surface water diverted from reservoirs in the Cordillera mountain range and the Tilata water system is based on groundwater withdrawal [5,24]. The El Alto system has the largest volume of treated water and supplies the rapidly expanding areas of El Alto and a portion of La Paz. The Achachicala and Pampahasi systems cover the remainder of La Paz. The Tilata system serves the part of El Alto not covered by the El Alto system, its supply volume being relatively small. During 2011, the total volume of water sent to these four treatment plants was $74.1 \times 10^6\,m^3$, among which the share of the El Alto system was 42.2%, the Tilata system 7.5%, and the Achachicala and Pampahasi systems were nearly equal (25.4% and 24.9%, respectively).

The catchments linked to each of the supply systems are illustrated in Fig. 1. The main source catchment of the El Alto system is the Tuni Lake catchment, which includes the Condoriri, Huayna Potosi, and Tuni catchments (Fig. 2). Because of the growing water demand for the El Alto system, a part of the supply to the system has been supplemented by the water transferred from Milluni Lake in the Milluni catchment since 2008. The line from Milluni Lake bifurcates to the El Alto system before connecting with the Achachicala system as shown in Fig. 1. The Achachicala system is supplied water from the Milluni catchment and the Choqueyapu catchment. The Choqueyapu River has no reservoirs linked with the treatment plant but the seasonal streamflow from the river has been used in the system. The Pampahasi system is connected to the Incachaca Lake and Hampaturi Lake reservoirs. These four catchments (Milluni, Choqueyapu, Incachaca, and Hampaturi) have limited or no substantial glacial cover (Fig. 1). The Taypichaca River catchment is included in the figure because we examined the availability of water from this catchment to adapt for the anticipated future water scarcity in La Paz and El Alto, although it is not currently serving any supply systems in La Paz and El Alto (Supplementary Fig. S1.1).

In this study, we specifically focused on the water supply and demand for the El Alto system, because it is the most rapidly growing area in La Paz and El Alto. In the El Alto system, the runoff from partially glacier-covered upstream catchments, i.e. the Condoriri, Tuni, and Huayna Potosi catchments (Table 1, Fig. 2), is diverted and stored in Tuni Lake (Supplementary Fig. S1.2). The land surface of each catchment is largely covered by un-vegetated soil and gravel. Figs. 1 and 2 show the distribution of glacier-covered areas obtained from Landsat Thematic Mapper images obtained during 2010 with the band ratio method verified by Liu et al. [21]. In these catchments, lakes and wetlands occur along the stream and/or on the hillslopes, and contribute to retardation of the runoff from glacial melt and snowmelt, gradually supplying the water.

The runoff from the Tuni catchment flows into Tuni Lake throughout the year without control while the runoff from the Condoriri and Huayna Potosi catchments is diverted to the lake through a channel connected to the stream running in each catchment (Fig. 2 and Supplementary Fig. S1.3) from November to April. Currently, a constant volume of water (nominal volume is $1\,m^3/s$) is released from Tuni Lake to the El Alto system. The excess volume of storage in the lake is discharged to the Condoriri River from the spillway. The capacity of Tuni Lake is summarized in Supplementary Table S1.1.

The Achachicala system covers the urban center of La Paz, and the system is supported by water from Milluni Lake storing runoff from the Milluni catchment (Fig. 1). The glacier contribution to the total runoff from the Milluni catchment is relatively small compared to that of the Tuni Lake catchment [39]. To adapt to increasing water demand in the El Alto system, the marginal part of the water storage has been transferred from Milluni Lake to the El Alto system since 2008.

2.2. Estimation of future water demand

The future water demand for the El Alto and Achachicala systems for domestic use was estimated based on the future population predicted by the cohort component method and provided values of supply coverage, unit water consumption, and non-revenue water rate (Supplementary Table 1.2) following the procedure shown in Supplementary Fig. S1.4. The cohort component method is among the most commonly used methods for population projection, and it considers fertility, mortality, and migration of each age- and sex-specific group. Because of the lack of statistics for fertility and mortality for each city, we alternatively used the data for fertility and mortality for the La Paz Department obtained from the Instituto Nacional de Estadística Bolivia (INE) (http://www.ine.gob.bo/), and the Demographic Health Survey or DHS (Encuesta Nacional de Demografía y Salud) conducted by the Ministry of Health and Sports and National Institute of Statistics (Ministerio de Salud y Deportes, Instituto Nacional de

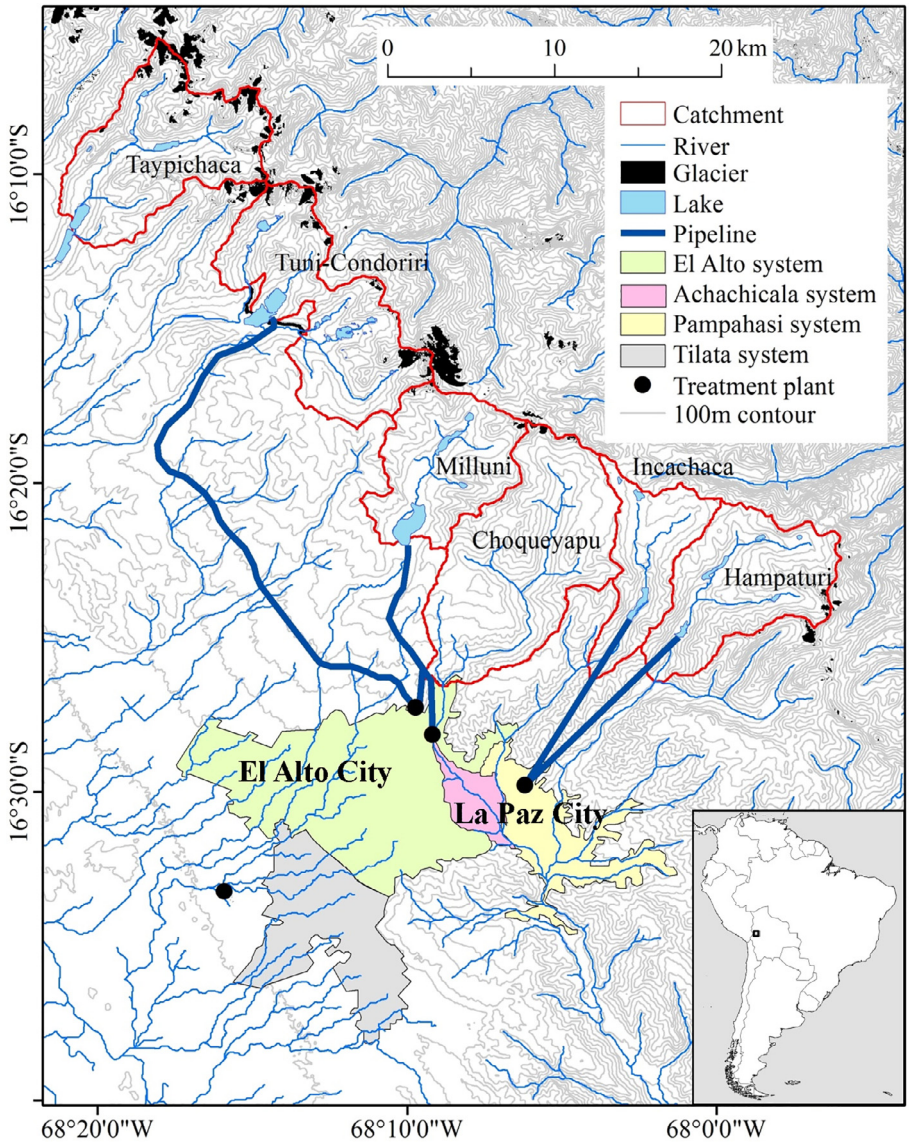

Fig. 1. Overview of current water supply systems for La Paz and El Alto and the source catchments in the Cordillera mountain range. The areal extent is shown by a black box in the inset. The link between reservoirs and treatment plants is simplified and does not follow the exact routes.

Estadística) [26] and WHO Bolivia (http://www.who.int/countries/bol/en). The net migration rate was calculated based on the population by age and sex [15,16], the birth rate obtained from DHS (2003, 2008) and the fertility obtained from INE (http://www.ine.gob.bo/). The method used for the projection was verified by comparing the population from the national census in 2012 and the estimated population by age and sex (population pyramid) for 2012, with the base population provided by the 2001 census data [15,16]. We assumed that the changing water availability does not affect the fertility, mortality, and migration [34], although the water availability is considered as a driver for migration and resulting regional and ethnic tension [33]. Given the base population from the 2012 census, the population in La Paz and El Alto was projected until 2036, which corresponds to the target year set in the master plan for portable water and sanitation developed by the MMAyA [24]. The total population in each city was allocated to each supply system, including the El Alto and Achachicala systems, based on the current ratio of population served by each system compared to the total population in each city. Then, the future water demand for domestic use in each system was calculated from the total population served by each system using parameters provided in Supplementary Table 1.2, which were set based on MMAyA [24]. The total demand for commercial, industrial, and other uses was estimated for the El Alto and Achachicala systems as a percentage of the total demand (10.3% and 41.2%, respectively), based on Zuleta [48] and the information provided by the Empresa Pública Social del Agua y Saneamiento (EPSAS), the municipal utility that operates the supply system.

Among demand-side options for sustainable water use, such as reducing consumption and repairing leaks, an improvement in water loss in the whole system was considered. To consider the effect of an improvement in non-revenue water rate (NRW), we assumed that the NRW linearly improves from the actual rate in 2011 to the target rate for 2036 set in the master plan [24].

2.3. Estimation of available water resources

We applied the semi-distributed conceptual model developed by Kinouchi et al. [18] and improved in this study (see Supplementary Information) to the Huayna Potosi, Condoriri, and Tuni catchments (Fig. 2, Table 1) to quantify the inflow from these catchments into Tuni Lake under current and future climatic conditions. The model parameters were updated from those used by Kinouchi et al. [18] (Supplementary Tables S3.1 and S3.2) based on calibration with daily

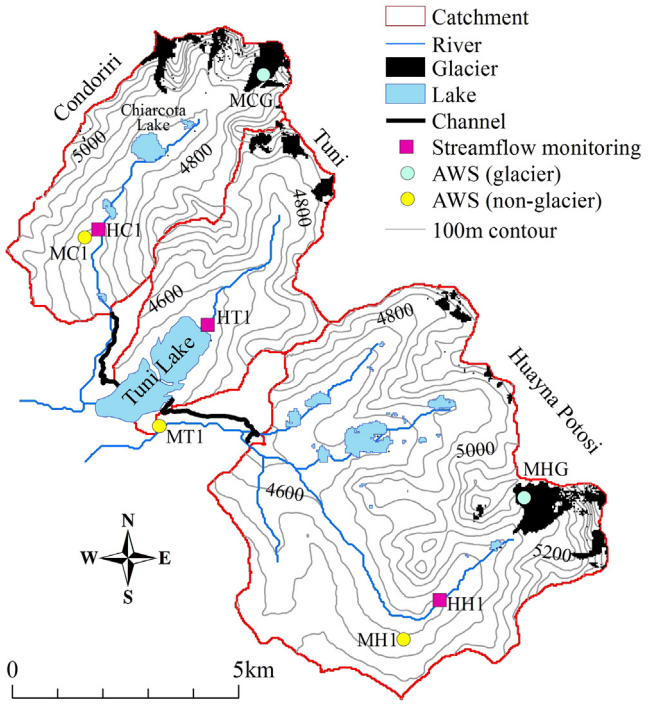

Fig. 2. Overview of the Tuni Lake catchment and the location of monitoring stations. The Condoriri catchment and the Huayna Potosi catchment are connected to Tuni Lake through the open channel. Glacier-covered areas were extracted from Landsat TM data acquired during May of 2010.

Table 1
Summary of three catchments from which the runoff is diverted to Tuni Lake.

Catchment		Huayna Potosi	Tuni	Condoriri
Area (km^2)	Total	7.99	9.72	16.07
	Glacier	1.46	0.51	1.19
	Lakes	0.044	0.00	0.354
	Wetlands	0.248	0.068	0.106
Percentage of glacier-covered area (%)		18.2	5.2	7.4
Mean annual precipitation between 2011 and 2017 (mm) measured at each AWS		627 (MH1, 4736 m a.s.l.)	577 (MT1, 4472 m a.s.l.)	744 (MC1, 4490 m a.s.l.)
Elevation (km a.s.l.)		4.7–6.1	4.4–5.4	4.4–5.6

streamflow observed at gauging stations HH1, HT1, and HC1 (Fig. 2 and Supplementary Fig. S3.6), the albedo on the glacier surface of the Huayna Potosi Glacier (MHG) and Condoriri Glacier (MCG) (Supplementary Fig. S3.7; and the water level in Chiarcota Lake (Supplementary Fig. S3.8). The daily lapse rate was provided from the air temperature observed at two automated weather stations (AWSs). The vertical gradient in precipitation was considered based on the monthly total precipitation observed at eight locations with an altitude ranging from 4490 m a.s.l. to 4870 m a.s.l. (not shown in Fig. 2). The inflow to Tuni Lake was calculated based on a given operational rule of diversion of streamflow from the Condoriri and Huayna Potosi catchments. Under the current rule, the full diversion of streamflow is assumed to start on November 1 and end on April 15.

The impact of climate change on the runoff from the three catchments and the release from Tuni Lake was quantified assuming several cases for the trend in air temperature and precipitation into the future, the volume of release from Tuni Lake, the glacier condition and the countermeasure (Table 2). The release from Tuni Lake was assumed constant throughout the projection period unless the water storage was below the dead capacity. In case 5, the release rate was adjusted to maximize the constant release while maintaining the storage volume in the lake greater than that of the dead capacity. In case 2, we assumed that there is no glacier in the Tuni Lake catchment to highlight the effect of glacial meltwater on modulating the drought situation, while actual glacier conditions were used for other cases (Fig. 2) as the initial condition and the glacierized area decreases depending on the volume of melted and sublimated glacier ice (see supplementary information). The no-glacier scenario was used by Baraer et al. [2] and Soruco et al. [39] for the same purpose, the latter being the application to La Paz and El Alto. In cases 5 and 7, the full diversion is assumed during the extended period to examine the effect of this immediate countermeasure. In cases 6 and 7, we used downscaled global climate model (GCM) outputs (MRI-AGCM) with the spatial resolution of 20 km [19]. The output of MRI-AGCM was used because of its high performance in reproducing the present weather conditions over South America and the high spatial resolution to well-resolve the Andes Mountains [19]. MRI-AGCM outputs for the SRES A1B scenario Nakicenovic and Swart [30] were statistically bias-corrected and downscaled for the period between 2020 and 2039 using the data from the AWSs (Fig. 2) in the Tuni Lake catchment (see Supplementary Information). The trends for cases 1 through 5 as shown in Table 2 were determined considering the long-term trend found in the selected GCM outputs and an analysis of historical data over the same region, based on the following overview.

The results of Seiler et al. (2013) show a median change in annual mean air temperature from 1961 to 90 to 2070–99 between 2.7 °C for SRES B1 scenario Nakicenovic and Swart [30] and 5.7 °C for RCP 8.5 scenario (Moss et al., 2010) among the five emission scenarios used in CMIP3 and CMIP5, which is equivalent to 0.25 °C decade^{-1} and 0.52 °C decade^{-1}, respectively. For annual precipitation, the projections of the individual GCMs varied so much that changes in the weighted ensembles were not statistically significant (Seiler et al., 2013). Similarly, no significant change in annual total precipitation was obtained by Thibeault et al. [40]. Urrutia and Vuille [41] indicated, using a regional climate model with the A2 scenario, that precipitation will decrease approximately 10% along the western slopes of the tropical Andes above 4000 m a.s.l. by the end of this century. Minvielle and Garreaud [27] suggested a significant reduction (10%–30%) in Altiplano precipitation by the end of this century.

Our analysis of GCM outputs for the RCP8.5 scenario [29] in nine models (GFDL-CM3, CSIRO-Mk3-6-0, CMCC-CM, HadGEM2-AO, MIROC5, MPI-ESM_MR, MRI-CGCM3, CNRM-CM5, and CCSM4) indicated an increasing trend in air temperature between 0.32 °C decade^{-1} and 0.6 °C decade^{-1}, with an average of 0.4 °C decade^{-1}. The relative change in annual precipitation in these outputs ranged from −0.42%/year to 0.4%/year with an average near 0 and the standard deviation equal to 0.27%/year, indicating no clear increasing or decreasing trend.

We also analyzed the annual precipitation and mean air temperature measured at the El Alto airport (16° 30′ 37″, 68° 11′ 55″) and obtained from the ERA-Interim dataset (291° 22′ 30″ – 292° 7′ 30″, S16° 7′ 30″ – S16° 52′ 30″) between 1985 and 2014. The measured and reanalyzed data showed a trend of 0.14 °C decade^{-1} and 0.29 °C decade^{-1}, respectively, but there was no significant trend in annual precipitation in both datasets. A comprehensive review by Rabatel et al. (2013) concluded that precipitation has not displayed a significant, spatially coherent trend in the tropical Andes since the middle of the 20th century.

Based on these reviews and analyses, we assumed that the air temperature will change in the future at a rate of 0.4 °C decade^{-1}, which is the average of the nine GCM outputs and near the average for RCP4.5 and RCP8.5 scenarios as shown by Seiler et al. [37] for cases 1 through 5. The trend in precipitation was set to 0 with an uncertainty range of ± 0.2%/year, which is considered in cases 3 (trend = +0.2%/year) and 4 (trend = –0.2%/year), reflecting a variety of trends found in different sources of current and future precipitation. The downscaled MRI-AGCM data used for cases 6 and 7 shows a trend of annual mean

Table 2
Scenarios used for quantifying available water resources for the El Alto system. dT is the trend of the annual mean air temperatured and dP is the relative change in annual precipitation. In cases 5 and 7, full diversion is assumed during the extended period, i.e. between Oct. 15 and Apr. 30.

Case No.	Climate condition during the projected period	Release	Glacier condition	Countermeasure
1	dT = 0.04 °C/yr, dP = 0.0%/yr	0.97 m^3/s	With glacier	None
2	dT = 0.04 °C/yr, dP = 0.0%/yr	0.97 m^3/s	W/o glacier	None
3	dT = 0.04 °C/yr, dP = + 0.2%/yr	0.97 m^3/s	With glacier	None
4	dT = 0.04 °C/yr, dP = − 0.2%/yr	0.97 m^3/s	With glacier	None
5	dT = 0.04 °C/yr, dP = 0.0%/yr	Adjusted	With glacier	Extended diversion period
6	Downscaled MRI-AGCM data	0.97 m^3/s	With glacier	None
7	Downscaled MRI-AGCM data	0.97 m^3/s	With glacier	Extended diversion period

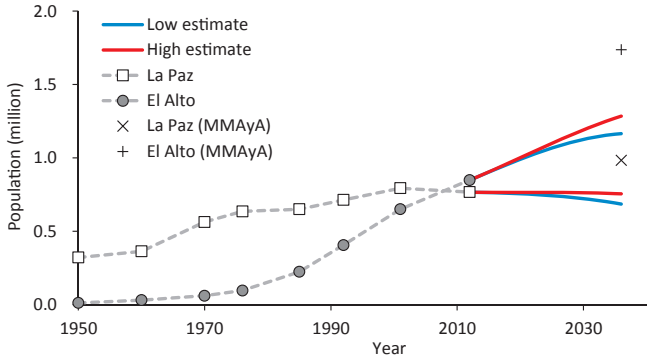

Fig. 3. Population change in La Paz and El Alto between 1950 and 2012 (census record) and from 2012 to 2036 (projected results). Projected curves show high and low estimates for each city. The future population reported by MMAyA [25] is plotted for each city.

air temperature and annual precipitation at each AWS ranging between 0.19 °C and 0.28 °C $decade^{-1}$ and between −0.65%/year and −0.43%/year, respectively (Supplementary Fig. S2.8). Although the underlying scenarios used to run MRI-AGCM (SRES scenarios) are different from those in CMIP5, Knutti and Sedláček [20] indicated that the projected global temperature change from CMIP5 models is remarkably similar to that from those used in CMIP3, and the similarity of the projected precipitation change in CMIP3 and CMIP5 is reassuring. Therefore, we considered that the output from MRI-AGCM can be used as one of the scenarios to compare with other scenarios defined by CMIP5 GCM outputs.

The water available from Tuni Lake to release into the El Alto system was evaluated by analyzing the temporal variation in water storage based on the water balance in the lake under a given condition of release (Table 2) considering inflow from three catchments, overflow from the spillway, and precipitation and evaporation over the lake surface. The evaporation was estimated using the bulk transfer method with measured and projected wind velocity, air temperature, and relative humidity at MT1 near the lake (see Supplementary Information). We assume that no water is released if the water storage in Tuni Lake is less than the dead capacity. The variation in water storage in Tuni Lake was verified under the current operational rule of intake and release. The future water supply was evaluated using the total volume of water released from Tuni Lake and transferred from Milluni Lake.

To meet the future increase in water demand for the El Alto system, we considered three options to increase the water supply, i.e. the transfer of marginal water from Milluni Lake, the extension of the period to divert streamflow from the Condoriri and Huayna Potosi catchments into Tuni Lake, and the use of stream water from the neighboring Taypichaca catchment. The transfer from Milluni Lake was assumed to increase, considering the decrease in demand for the Achachicala system, as explained in the subsequent section. The extended diversion from the current source areas could be the most practical option. The runoff from the Taypichaca catchment is considered as one of the new water resources [5] because of the advantage of a nearer location to La Paz and El Alto and the larger catchment size with a potentially large volume of glaciers. However, the water availability from the catchment has never been analyzed or reported. Here, we apply the semi-distributed model to the Taypichaca catchment to quantify the water resources potentially available from the catchment under future climate conditions.

The simulation period covers from 2011, when our weather monitoring started, to 2036, the target year of the master plan [24]. All of the future scenarios in Table 2 utilize the weather data obtained from June 2011 to July 2017. Under cases 1 through 5, meteorological forcing for the simulation was generated based on the observed weather conditions between 2011 and 2017 with the trend in air temperature and precipitation in each case added for the following period from August 2017 until August 2037. For cases 6 and 7, the observed weather data were spliced on the downscaled GCM output covering the period between 2020 and 2039 (see Supplementary Information). The annual water availability was calculated for each hydrological year, which was defined as starting in September and ending in August [35].

3. Results

3.1. Change in population and water demand in the future

The result of the population projection using the cohort component method is shown in Fig. 3. The total population in La Paz is estimated to decrease from 0.77 million in 2012 to 0.69–0.75 million in 2036, while the population in El Alto significantly increases from 0.85 million in 2012 to 1.17–1.28 million in 2036. Our result shows a reasonable trend for each city, compared to the future population reported by MMAyA [25] (Fig. 3), which was obtained from the exponential growth model considering the population changes only until 2001. The mean growth rate of the total population during 2012–2036 was calculated and ranged between −0.46%/year and −0.07%/year for La Paz and 1.33%/year and 1.74%/year for El Alto. As a result, the total population in La Paz and El Alto in 2036 is estimated to increase by 14.6 and 26.2% for low and high estimates, respectively, relative to the total population in 2012. The mean growth rate of the total population during 2012–2036 is calculated to be between 0.57%/year and 0.98%/year, which is less than that obtained from the future population reported by the MMAyA (2.2%/year). The decreasing trend in population in La Paz is a result mainly of a decreasing birth rate and net outbound migration. The decreasing population growth rate in El Alto is mainly a result of the decreasing birth rate. In addition, we found that the population pyramid is projected to shift from a current expanding shape to a contracting (La Paz) or stationary (El Alto) shape (Supplementary Fig. S1.5).

The result of the population served by the El Alto and Achachicala systems, which was allocated from the projected population in La Paz and El Alto, is shown in Supplementary Table S1.3 for selected years. The corresponding result of water demand is shown in Table 3, indicating that the water demand for the El Alto system will increase by 15–25% in 2036 compared to the demand in 2011, with the range depending on the population estimate. Table 3 includes the water

Table 3
Actual and projected water demand for the El Alto and Achachicala systems and transfer from Milluni Lake to the El Alto system (unit: 10^6 m^3 year^{-1}). Percent value indicates the relative increase from the demand in 2011. The transfer from Milluni Lake shows a possible range estimated from the projected demand for the Achachicala system and the total water resources available from Milluni Lake and the Chokeyapu River.

Year	Demand for El Alto system				Demand for Achachicala system		Transfer from Milluni Lake
	Improved NRW		Current NRW				
	Low population	High population	Low population	High population	Low population	High population	
2011	32.4				18.8		2.8
2020	34.3 (6%)	34.6 (7%)	39.8 (23%)	40.2 (24%)	16.5 (−12%)	19.1 (1%)	1.09–3.69
2025	35.2 (9%)	36.2 (12%)	42.9 (32%)	44.1 (36%)	15.5 (−18%)	19.1 (1%)	1.08–4.62
2030	36.5 (13%)	38.4 (19%)	44.6 (38%)	46.8 (44%)	15.1 (−20%)	19.0 (1%)	1.13–5.00
2036	37.2 (15%)	40.6 (25%)	45.5 (40%)	49.6 (53%)	14.6 (–23%)	18.9 (3%)	1.24–5.58

demand obtained with the assumption that the current condition of water loss (NRW) continues into 2036 without improvement, resulting in an increase of 40–53%. The water demand for the Achachicala system in 2036 will decrease by 23% or slightly increase by 3% compared to that in 2011, depending on the population estimate. The effect of improving water loss (a comparison between the cases of improved NRW and current NRW) increases towards the end of the projection period, resulting in a water saving of 8.3×10^6 m^3 and 9.0×10^6 m^3 for the low and high population estimates, respectively (Table 3). If the current water losses were not improved in accordance with the master plan, a serious increase in water demand due to population growth would be expected. The uncertainty range of the water demand for the El Alto system resulting from population projection increases from approximately 2022 as can be seen in Fig. 5.

3.2. Current and future runoff and water storage

The performance of the model in reproducing the current flow regime was confirmed by comparing the simulated monthly flow depths (monthly total streamflow volume divided by the catchment area) with those observed at three gauging stations (Supplementary Fig. S3.6). The performance was judged to be “very good” or “good” using three metrics, i.e. Nash-Sutcliffe efficiency (NSE), ratio of the root mean square error to the standard deviation of measured data (RSR) and percent bias (PBIAS) Moriasi et al. [28] (see supplementary Table S3.3). The streamflow is greater during the wet season between November and April for the Tuni and Huayna Potosi catchments, while for the Condoriri catchment limited streamflow was observed during November and more flow was apparent during May because of the temporary storage of runoff in the relatively large natural lakes in the catchment. This characteristic suggests that more water can be diverted into Tuni Lake by extending the period for diversion, particularly from the Condoriri River.

The simulated inflow to Tuni Lake was verified using the water storage volume (converted from the water level) observed by the EPSAS and Prof. M. Umeda from Tohoku University, Japan (personal communication) for the period between 2011 and 2017 (Fig. 4(a)). In the simulation, the water volume released from the lake (nominal volume = 1 m^3/s) was adjusted to 0.97 m^3/s for better agreement with the observed storage volume. The storage volume shows a periodic variation with its annual minimum occurring during November or December while a certain volume of water ($7.6–9.6 \times 10^6$ m^3) remained even during the serious drought year from 2015 to 2016. The simulated water balance in Tuni Lake indicates that a nearly constant release has been attained and the overflow of excess storage was simulated in each hydrological year between 2012 and 2015 (Fig. 4(b)). The simulated volume of water supply during August 2011 and July 2017 (release from Tuni Lake + transfer from Milluni Lake = 33.4×10^6 m^3/year) is nearly the same as the water demand quantified by MMAyA [24] for 2011 (32.4×10^6 m^3/year) (Table 4). Fig. 4 shows the projected results of water storage and water balance in the lake for case 1 and case 6, indicating the periods that the storage empties and the release is reduced or even 0 for a certain period (the maximum reduction occurs in October). The reason for the decreasing trend in storage found for case 1 is the decreasing runoff from glacier-covered areas, including glacier melt, snowmelt, and subsurface runoff, which coincide with the stage of negative runoff change for retreating glaciers in the same region [2,14]. Similarly, for case 6, the influence of decreasing glacial meltwater combined with the larger variability in precipitation (Fig. 4(h)) resulted in a greater reduction in the release as time passed (Fig. 4(f)).

The effect of glacial melt can be approximately estimated as the difference in the inflow to Tuni Lake between case 1 and case 2, which indicates an approximately 6.1% contribution of glacial meltwater to the annual inflow during 2011 and 2038, and a 10.2% contribution during 2011 and 2016. Soruco et al. [39] indicated that more than 20% of the discharge could be lost with complete disappearance of all glaciers in the Tuni Lake catchment. The different estimates may be mainly because of the difference in the period of analysis (less contribution is likely during recent periods because of shrinking glaciers) and the limited period of streamflow diversion from the Condoriri and Huayna Potosi catchments (the contribution increases to 10.6% during 2011 and 2016 if the annual total runoff is used). From isotope analysis, Guido et al. [13] estimated a higher percentage of glacial meltwater contribution for the storage in Tuni Lake, possibly because glacial meltwater contains some fraction of melted old ice in addition to melted recent snow.

3.3. Projected water supply for the El Alto system and a comparison to the water demand

Fig. 5 shows the projected water supply for the El Alto system, which is the sum of release from Tuni Lake and the transfer from Milluni Lake (the maximum volume in Table 3 was used), under different scenarios of climate change, glacier cover, and adaptation measures. As can be seen in the figure, the annual water demand for the system for different population estimates and NRW improvement scenarios was also included. The difference in water supply among the cases is mainly because of the different volumes of inflow to Tuni Lake, and the influence of precipitation and evaporation over the lake's surface is relatively small (Table 4). The increasing trend in supply is clearer for cases 3 and 5 because of the sufficient inflow to Tuni Lake to sustain the constant release (0.97 m^3/s) throughout the year and the increasing volume of transfer from Milluni Lake (the same condition applies for all cases), which is a result of the decreasing demand on the Achachicala system. Other cases show a decrease in supply during some periods because of insufficient storage to release the specified volume of water (0.97 m^3/s) from Tuni Lake.

The results for cases 3 and 4 indicate a possible range of impacts caused by the uncertainty in the trend in precipitation. The result of case 4 shows three periods of decreased supply, which were not found in case 3, caused by the periodically lower precipitation with a superposed decreasing trend during the 20 years from 2017 to 2036. As a

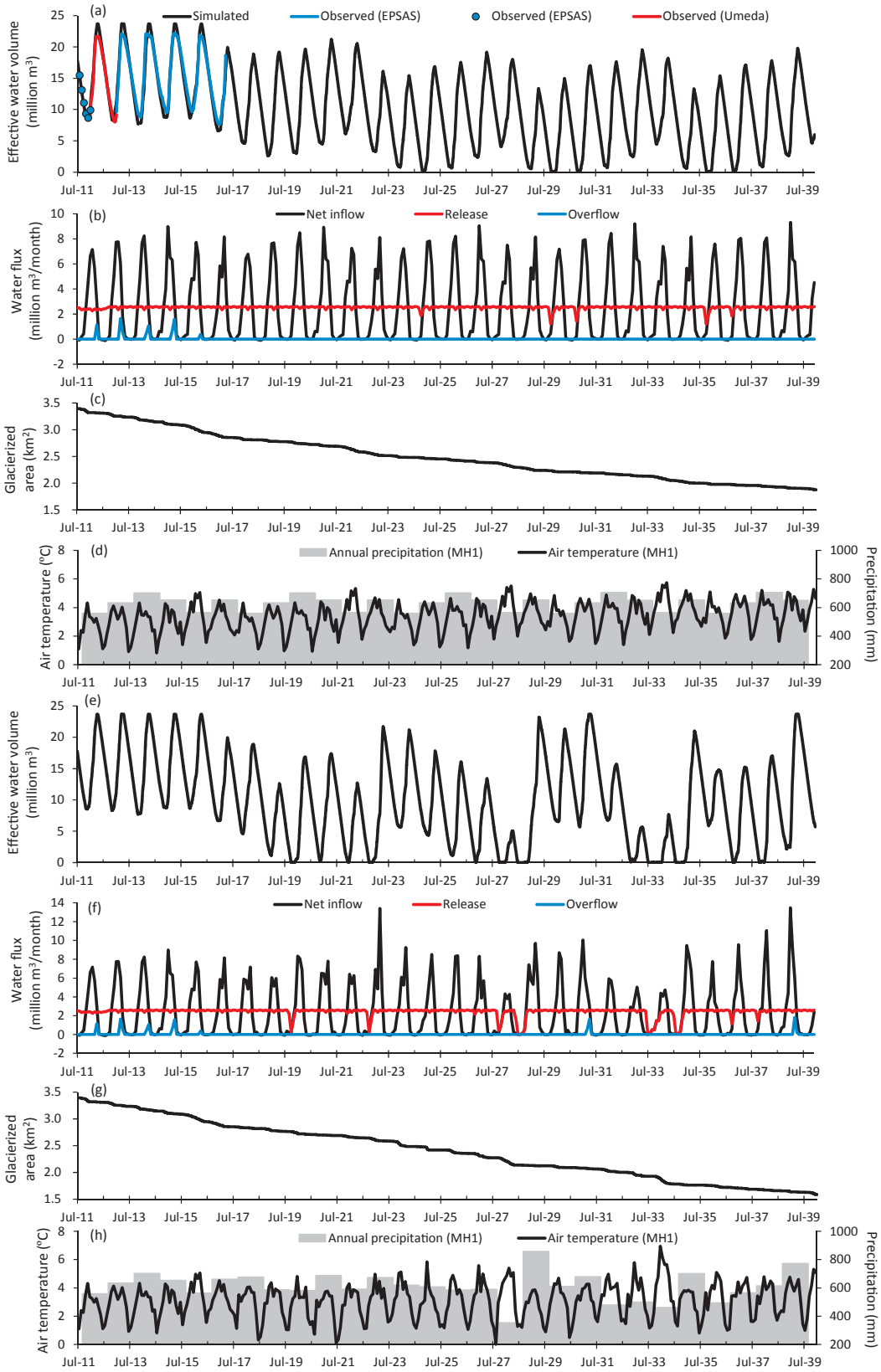

Fig. 4. Water storage and water balance in Tuni Lake for case 1 ((a) and (b)) and case 6 ((e) and (f)). The comparison between simulated and observed water storage is shown in (a). The simulated total glacierized area in the Tuni Lake catchment for case 1 and case 6 is shown in (c) and (g), respectively. Meteorological conditions (observed air temperature and precipitation) for case 1 and case 6 are shown in (d) and (h), respectively. The diversion from the Condoriri and Huayna Potosi rivers is assumed to start on November 1 and end on April 15 during every hydrological year.

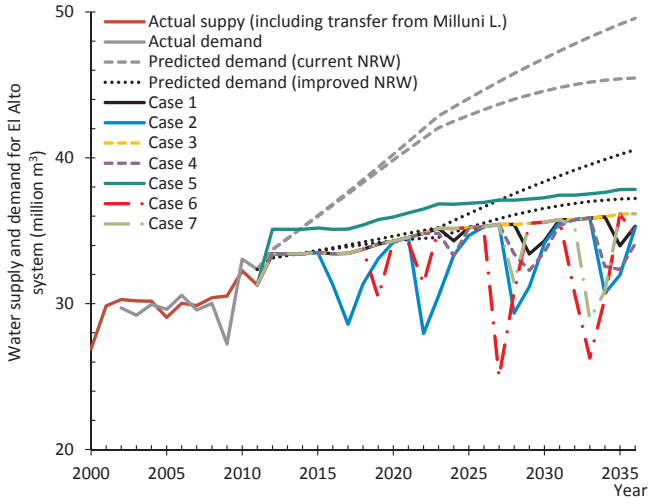

Fig. 5. Actual and predicted water supply and demand for the El Alto system between 2000 and 2036. The actual supply and demand is based on the information included in the masterplan [24]. Gray dashed lines and black dotted lines indicate the water demand for the current and improved NRW, respectively, with high and low population estimates.

Table 4
Water balance in Tuni Lake between August 2011 and July 2017, water transfer from Milluni Lake in 2011 and demand for the El Alto system in 2011. The water balance is based on the simulated runoff and operational rule for diversion and release. The volume of transfer and demand is provided from information included in the master plan [24].

Water balance in Tuni Lake (10^6 m^3/year)					Transfer from Milluni Lake (10^6 m^3/year)	Demand (10^6 m^3/year)
Inflow	Precip. – Evapo.	release	Overflow	Storage change		
30.9	0.6	30.6	1.2	–0.3	2.8	32.4

result, the water supply for case 4 decrease to much less than the demand even for the case of improved NRW with low population estimates.

The contribution of meltwater for modulating the drought situation was found by comparing the results for case 1 and case 2 as shown in Fig. 5. The result for case 2 shows a frequent failure in supplying the specified volume of water due to the lack of glacial meltwater runoff, which would typically occur during the early wet season from October to early December. Although the contribution of glacial meltwater runoff to the storage in Tuni Lake was estimated to be approximately 10% during the period 2011–2016, Although the percentage is not so high on average, a significant influence on supply could be caused by the lack of glacial meltwater during some years. This is mainly because of the reduced runoff during the period when the glacial meltwater mostly contributes to the streamflow, i.e. from September to November, depending on the weather conditions in each melting season.

The result for case 6 shows a greater decrease in supply in 2027 and 2033 because of a prolonged period of failure in keeping the storage above the dead capacity (Fig. 4(f)). The reason for the serious failure is the lesser amount of precipitation during 2027 and 2031–2033, and the decreasing contribution from glacial meltwater as glacial retreat progresses.

The projected water supply for the different future scenarios (cases 1, 3, 4, and 6) are nearly in a critical balance with the demand until approximately 2023, even though a serious decrease in supply was found for case 6. After 2023, the supply deficit continues to increase, even against the case of the lowest demand estimate (a low population and improved NRW). If the projected demand follows the high estimate for improved NRW, the supply deficit is expected to be more serious for these cases and an extremely large shortage was found for some years for case 6.

The results of cases 5 and 7 show the effect of an extended period of streamflow diversion from the Condoriri and the Huayna Potosi rivers. For case 5, a greater constant release becomes possible (1.023 m^3/s) without emptying the storage and the balance between the demand for the low population estimate with improved NRW is maintained throughout the simulation period, while the demand for the high population estimate is not satisfied after 2027. Similarly, for case 7, the extension of the diversion period resulted in more years of constant release (0.97 m^3/s) without failure and an increase in the mean annual supply compared to that for case 6.

The extension of the diversion period requires no additional cost in terms of infrastructure (Supplementary Fig. S1.3), thus it can be an immediate and effective measure to prepare for the expected decrease in the lake storage. However, the coordination of existing water rights among local people and compensation and support for downstream stakeholders is necessary, particularly for smallholder farmers that especially vulnerable to climate change and water shortages [23].

3.4. Balancing the water supply and demand under climate extremes and uncertain socio-economical situations

The uncertainty of water supply and demand related to the projection of climate change, population estimates, and implementation of countermeasures needs to be considered to secure water for this rapidly growing region.

For example, the water shortage in the El Alto system is predicted to become more serious if the water losses in the supply system are not reduced as planned in the master plan [24] as shown in Fig. 5 (gray dashed lines). Although a serious shortage in water supply has not chronically occurred thus far, implying continuous progress in NRW improvement, temporary water rationing has sometimes been enacted. Therefore, future progress in NRW improvement is still uncertain and will be affected by economic and political situations.

In previous sections, we assumed an increase in transfer from Milluni Lake because of the projected decrease in demand for the Achachicala system. The effect of the transfer was considered while each scenario in Table 2 was examined (Fig. 5). However, this component of supply also depends on the climatic conditions and a certain range of uncertainty exists for the water available from Milluni Lake. Therefore, a more sophisticated method will be necessary in a future work to better quantify the marginal water from the Achachicala system.

The extension of the diversion period is likely to be among the most promising measures to increase the natural water storage as shown in Fig. 5 (cases 5 and 7), although it must be carefully implemented considering the existing water rights and the effect on stakeholders in downstream areas.

The results shown in Fig. 5 clearly indicate a prolonged period of failure in supplying water under the extreme climatic conditions of the future. Therefore, other options are examined here for securing water under uncertain and extreme situations of climate, supply, and demand, by quantifying the water resources available from the neighboring undeveloped Taypichaca catchment (Fig. 1).

Fig. 6 shows the runoff from the Taypichaca catchment simulated using the same glacio-hydrological model used in this study. Because the hydro-meteorological conditions over the Taypichaca catchment are not available, we applied the same meteorological conditions used for the hydrological simulation for each sub-catchment of Tuni Lake to predict the runoff from the Taypichaca catchment for cases 3 and 6. In both cases (Fig. 6(a) and (b)), the projected annual runoff shows a certain range of uncertainty mainly caused by the difference in the total amount of precipitation measured in each sub-catchment (Table 1), providing a low estimate when the data of the Huayna Potosi catchment

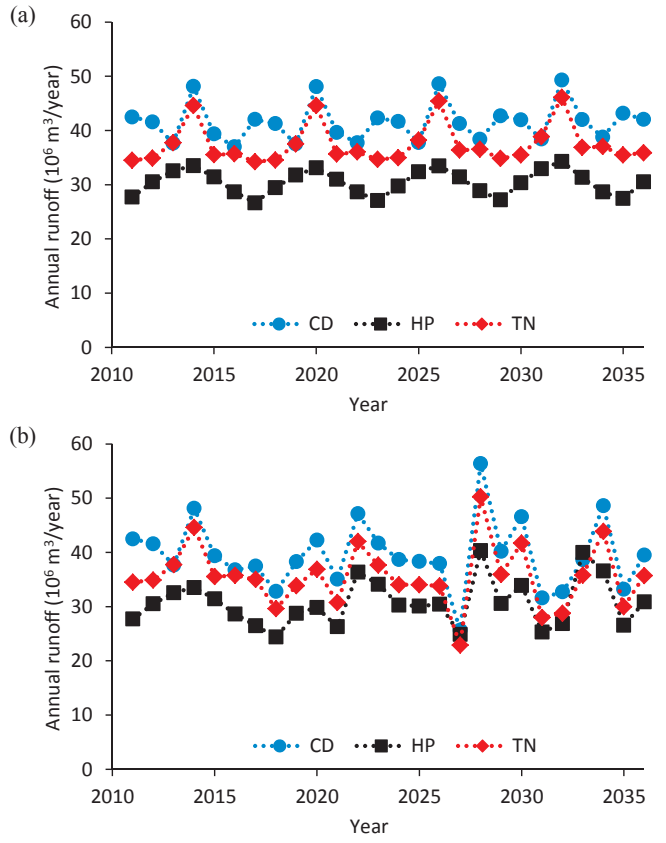

Fig. 6. Simulated result of annual runoff from the Taypichaca catchment for (a) case 4 and (b) case 6. The same local meteorological conditions used for the simulations for the Condoriri catchment (CD), the Huayna Potosi Catchment (HP), and the Tuni catchment (TN) were applied.

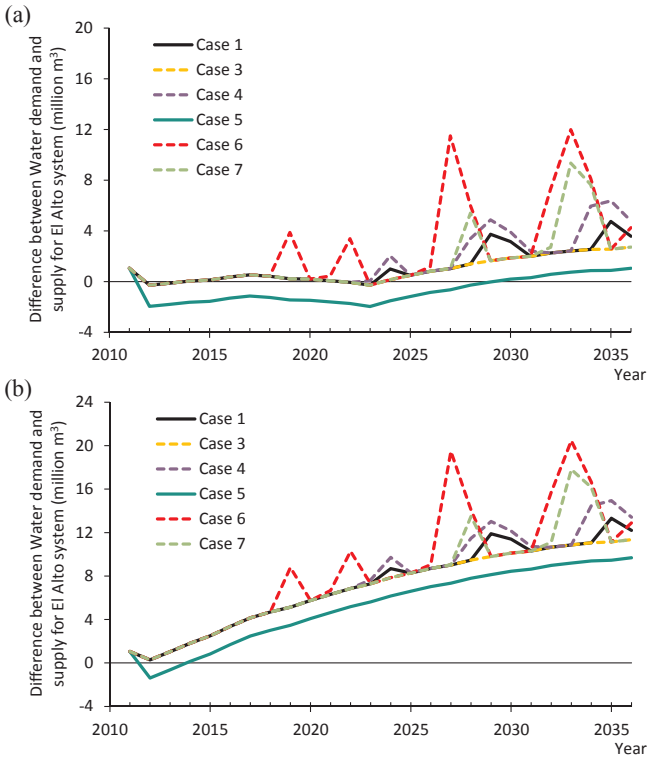

Fig. 7. Difference between projected water supply and demand for the El Alto system between 2011 and 2036. The projected demand is based on the mean population estimate for (a) improved NRW and (b) current (unimproved) NRW.

were used. Among the cases simulated, the lowest annual runoff was estimated to be 24.4×10^6 m^3/year, which is greater than the shortage estimated from the results shown in Figs. 5 and 7.

Fig. 7 summarizes the gap between the projected water supply and demand for the El Alto system for each case examined in the previous section to compare to the annual runoff available from the Taypichaca catchment. As shown in Fig. 7(a), the water shortage is small or not serious until approximately 2023 for the cases with the demand of improved NRW (except for case 6) and the supply exceeds the demand for case 5 until 2029. If the NRW is not improved as planned, a continuous increased water shortage was calculated with an additional water deficit caused by the extreme climatic conditions assumed in the hydrological simulations (Fig. 7(b)). Considering the range of possible annual runoff from the Taypichaca catchment (Fig. 6), it was found that the deficit is supplemented for both cases of NRW improvement if the minimum amount of the runoff from the Taypichaca catchment is assumed to be fully available (24.4×10^6 m^3/year). For the projected water shortage under the improved NRW situation (Fig. 7(a)), it is expected that only a small portion of runoff from the Taypichaca catchment is necessary to compensate for the deficit if the extended diversion from the Condoriri and Huayna Potosi catchments is combined (less than 2×10^6 m^3/year and 10×10^6 m^3/year for cases 5 and 7, respectively). For the case of an unimproved NRW with the mean population estimate (Fig. 7(b)), a disastrous drought would be avoided if a relatively large amount of runoff ($10–20 \times 10^6$ m^3/year) can be transferred from the Taypichaca catchment to the El Alto system.

The expansion of the Taypichaca Lake reservoir (Supplementary Fig. S1.1) is expected to increase its capacity to 18.07×10^6 m^3 [5], in which the supply deficit under a less improved NRW condition is likely to be supplemented. However, because the inflow to the Taypichaca Lake Reservoir is variable, the storage can be insufficient as seen in the case of Tuni Lake under extreme weather conditions (Fig. 4).

Regarding this new water source area, there may be conflicting issues between local stakeholders and authorities (MMAyA and EPSAS) regarding the existing water rights and the compensation for any losses and damages incurred resulting from the water transfer. For better preparation in addressing a serious water shortage in La Paz and El Alto while minimizing the effect on current water users, a well-designed allocation of storage in Taypichaca Lake is very much required for adapting to serious drought throughout the region under extreme and variable climatic conditions that could occur in the foreseeable future.

4. Conclusions

The future water supply and demand for the El Alto system, the most rapidly growing area of La Paz and El Alto, Bolivia, was estimated for the first time based on population projections and the glacio-hydrological simulations of runoff from source catchments, and measures for adapting to future water scarcity were examined.

The population in La Paz is projected to slightly decrease, while the population in El Alto is expected to increase, by 2036. Accordingly, the water demand for the El Alto system is projected to increase by 15–53% compared to the demand of 2011, depending on the scenario for the water loss in the supply system and population estimates.

A first-order prediction of the supply for the El Alto system from Tuni Lake was done under climatic conditions dictated by given trends and the downscaled GCM output with a detailed operational practice of the supply system. We found that even for the lowest demand estimate, the water deficit is likely to increase beginning in the mid-2020 s, particularly for a case based on the downscaled GCM output that includes larger variability and a decreasing trend for precipitation. Thus, water transfer from the neighboring Achachicala system through Milluni Lake is indispensable to sustain the supply that cannot be covered by releases from Tuni Lake, although it is not sufficient. An

extended period of diversion of runoff to Tuni Lake was found to be effective in increasing the supply to the El Alto system, resulting in a sustained water balance until 2027, even for the high estimates of population under an improved NRW. Because large uncertainty was found for the balance between the water supply and demand, depending on the scenarios for population growth, NRW improvement, and climate variability and trend, we examined the water availability from the Taypichaca catchment to prepare for serious drought. We showed that the transfer of runoff from the Taypichaca catchment would greatly aid in compensating for the large deficit of supply from the El Alto system under various uncertain situations.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasec.2019.100025.

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